GEOTECHNICAL DESIGNS OF THE INCHEON BRIDGE

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Abstract: *Incheon Bridg, 18.4 km long sea-crossing bridge is making an epoch of long-span bridge designs thanks to the fully application of the AASHTO LRFD (load & resistance factor design) to both the superstructures and the substructures. A state-of-the-art of the geotechnologies which were applied to the Incheon Bridge construction project is introduced. The most Large-diameter drilled shafts were penetrated into the bedrock to support the colossal superstructures. The bearing capacity and deformational characteristics of the foundations were verified through the world's largest static pile load test. 8 full-scale pilot piles were tested in both offshore site and onshore area prior to the commencement of constructions. Compressible load beyond 30,000 tonf pressed a single 3 m diameter foundation pile by means of bi-directional loading method including the Osterberg cell techniques. Detailed site investigation to characterize the subsurface properties had been carried out. Geotextile tubes, tied sheet pile walls, and trestles were utilized to overcome the very large tidal difference between ebb and flow at the foreshore site. 44 circular-cell type dolphins surround the piers near the navigation channel to protect the bridge against the collision with aberrant vessels. Each dolphin structure consists of the flat sheet piled wall and in-filled aggregates to absorb the collision impact. Geo-centrifugal tests were performed to evaluate the behavior of the dolphin in the seabed and to verify the numerical model for the design. Rip-rap embankments on the seabed are expected to prevent the scouring of the foundation. Prefabricated vertical drains, sand compaction piles, deep cement mixings, horizontal natural-fiber drains, and other subsidiary methods were used to improve the soft ground for the site of abutments, toll plazas, and access roads. Light-weight backfill using EPS blocks helps to reduce the earth pressure behind the abutment on the soft ground. Some kinds of reinforced earth like as MSE using geosynthetics were utilized for the ring wall of the abutment. Soil steel bridges made of corrugated steel plates and engineered backfills were constructed for the open-cut tunnel and the culvert. Diverse experiences of advanced designs and constructions from the Incheon Bridge project have been propagated by relevant engineers and it is strongly expected that significant achievements in geotechnical engineering through this project will contribute to the national development of the long-span bridge technologies remarkably.*

Keywords: Incheon Bridge, geotechnical engineering, foundations, drilled shafts, LRFD, ship impact protect

1. INTRODUCTIONS

Although superstructures of the bridge are multifarious, all the foundations consist of large diameter drilled shafts. Drilled shaft pile foundations were penetrated into the bedrock to support the colossal superstructures. The bearing capacity and deformational characteristics of the foundations were verified through the world's largest static load test using 8 full-scale pilot piles. A single pile-bent type foundation system was selected as well as the pile-cap type foundations.

Geotextile tubes, tied sheet pile walls, and trestles were utilized to overcome the very large tidal difference between ebb and flow at the foreshore site. 44 circular-cell type dolphins surround the piers near the navigation channel to

protect the bridge against the collision with aberrant vessels. Each dolphin structure consists of the flat sheet piled wall and in-filled aggregates to absorb the collision impact. Rip-raps are spread around the pile to prevent the scouring of the foundation. Prefabricated vertical drains, sand compaction piles, deep cement mixings, horizontal natural-fiber drains, and other subsidiary methods were used to improve the soft ground for the site of abutments, toll plazas, and access roads.

2. DESIGNS AND CONSTRUCTIONS OF THE FOUNDATION

New design scheme has been being implemented for the private investment section which occupies most of offshore part of the Incheon Bridge according to the project performance requirement (PPR) by the agreement between the government and the private concessionaire. PPR prescribed that the bridge design should comply with AASHTO LRFD (load & resistance factor design) specification. Incheon Bridge is the first case of the AASHTO LRFD applications to both the superstructures and the substructures in Korea.
Basic concept of the LRFD can be described as following equation. Qi is nominal load and R_i is nominal resistance.

$$\Sigma\, r_i\, Q_i \leq \Sigma\, \phi_i\, R_i \qquad (1)$$

Where, r_i is load factor and ϕ_i is resistance factor.

On the other hand, Korea Highway Bridge Design Code (KHBDC) was adopted for the government financed section. Geotechnical design according to the KHBDC is based on the allowable stress design (ASD) concept. This duality of the design philosophy in one bridge is another trial to conquer for geotechnical engineers. Some countermeasures were introduced to guarantee the reliability of the design by the LRFD concept. An independent design check on the tender design by the LRFD was carried out not only by a foreign bridge specialist engineer but also by a domestic expert consultant. They reviewed the design based on LRFD and KHBDC respectively. And detailed designs by the contractor were checked and certified by checking engineers prior to be submitted to the design supervisor (DS). DS has reviewed the checked design details and submitted it to the government after modifications. KEC, as the government position has approved the final design through the design deliberation committee. The construction supervisor (DS) selected by KEC has stated his opinions about the design to the deliberation committee.

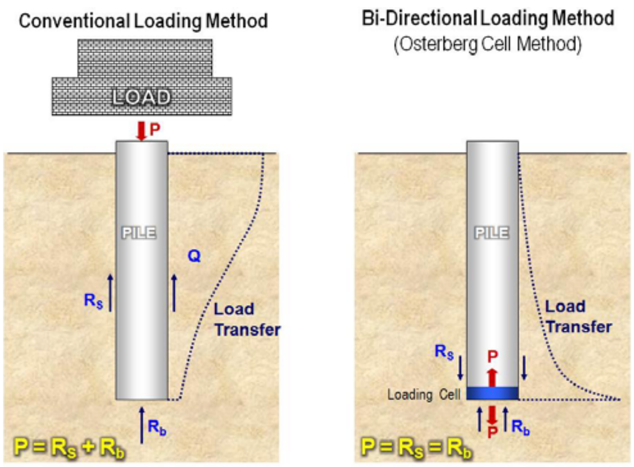


Figure 1. Conventional load test vs. bi-direction load test

Figure 2. Offshore pilot pile during the O-cell test

A number of full-scale static pile load tests were conducted for both the offshore section and the onshore sections not only to determine site specific load resistance factors in the LRFD implemented sections but also to remove any

excessive margin of the stability in the ASD implemented sections. 8 pilot piles were tested in order to establish criteria for bearing capacity evaluation by bi-directional loading method (Figure 3). We made a new world record static load test achieving 31,350 tf on a single 3.0 m diameter foundation pile near the cable-stayed sites (Figure 4). The test was conducted off-shore utilizing the Osterberg Cell test. We also experimented 3 testing piles with multi-level loading cell system to verify the side resistance varying according to the depth and the ground type. And during the constructions, an additional proof load test was conducted to confirm the design assumptions in addition to a series of lateral load tests on three reduced-scale piles and nine as-built piles at the site to confirm the lateral load carrying capacity. For the bridge section constructed by FSLM, the load-transfer characteristics were also examined by instruments installed at a pile with pile-bent to confirm whether or not the load from the supper structure is transferred to the foundation.

The estimation of bearing capacity and settlement of rock socketted drilled shafts was carried out based on the understanding of the site condition, the ground properties and pile load test results. The results of the load tests were thoroughly analyzed by a number of experts to determine the resistance factor, giving a unique opportunity to improve the current LRFD concept in Korea. External experts including an eminent professor of Seoul National University joined in the evaluating of resistance factors. Table 1 shows the resistance factors for the rock embedded drilled shafts of the Incheon Bridge (Cho et al., 2006; Kim et al., 2006).

Table 1. Resistance factors for the bearing layer of the drilled shaft in the Incheon Bridge

		Weathered Rock			Soft Rock	Hard Rock
		A*	B*	C*		
Strength Limit State	Side Resistance	0.50	0.75	0.70	0.70	0.65
	End Bearing	-	0.5		0.60	0.50
Ultimate Limit State	-	0.95				

* classification according to the SPT results. (d=penetration depth for 50 blows during the standard penetration test)
A : 15 cm ≤ d < 10 cm, B : 10 cm ≤ d < 5 cm, C : 5 cm ≤ d

In determining the side resistance of piles with rock sockets, the skin friction of overlying soil deposits and steel casing pips was neglected. The 1% of pile diameter criterion was used to determine the resistance of the pile. For cases where the pile shaft displacement exceeded 10 mm, the frictional resistance was also considered in addition to the end bearing capacity for the bearing capacity estimation. This means, because the bearing mechanism has been proved that the weathered rock and the soft rock were ductile in shear by the load tests, total resistance of rock socket was calculated as the sum of the side resistance and the end bearing. However, resistance in hard rock layer was separately applied according to settlement criteria (10 mm).

Fast track method applied in this project is innovative measures to save the construction time. This is described as a process of design and construction in parallel. The sequence of Design-Purchase-Contract-Construction was generally applied until now on. Each stage of fast track could be partially conducted at the same time so that the construction period can be reduced, and benefit of opportunity cost and service profit can be increased. Incheon Bridge project consists of 20 different design packages which cover from tests and investigations to design completion.

1,431 drilled shafts whose diameter was up to 3.0 m were installed to support this long span bridge. The drilled shafts were constructed by a number of methods considering the ground conditions and the efficiency. They were Beneto method, reverse circulation drilling (RCD) method, earth drilling method, casing-pipe rotator method, and etc.. During the construction of drilled shafts, steel casing pipes were first installed in the decomposed rock layer using a vibratory hammer with concurrent excavation of the materials inside of the casing pipes. Tip elevation of the drill shaft was determined based on the rock quality inspection procedure specified by KEC. Intensive inspections were done especially for the single pile-bent system foundation. After excavation, excavated soils and rock debris were removed and a rebar cage was installed after which underwater concrete was poured using a

tremie pipe to complete a shaft. Rebar cages for the pile were manufactured using an automated fabrication system for the first time in Korea.

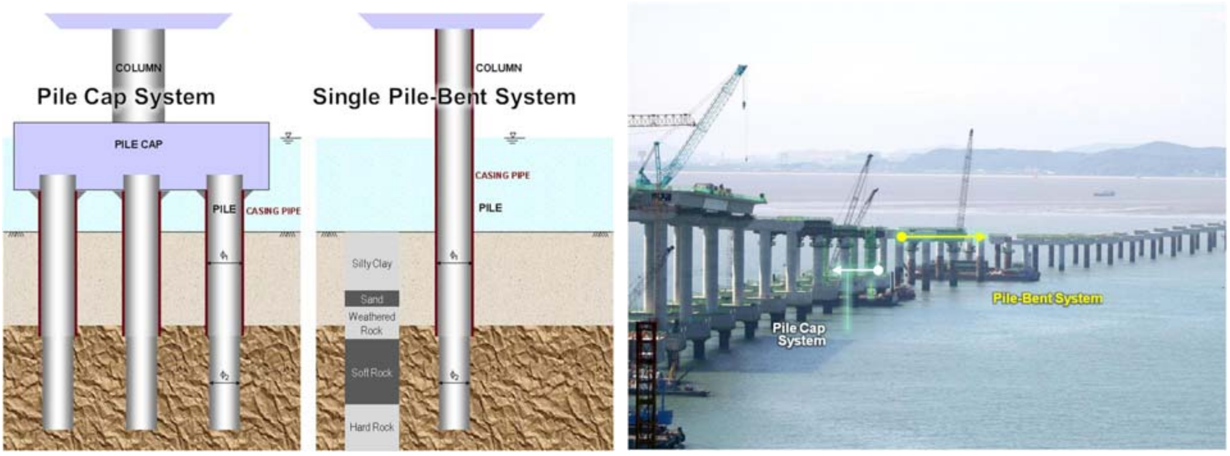


Figure 3. Types of the drilled shaft foundation

Figure 4. Drilled shaft constructions (offshore and onshore)

A cross-hole sonic logging (CSL) was conducted to check the pile integrity. Because single pile-bent foundation has relatively low redundancy, all of them were tested while sampling tests were adopted for pile-cap type foundations (Jung et al., 2007). In addition to the drilled shafts, a number of steel pipe piles with 2.4 m and 1.8 m in diameter were installed for the overhead crane foundation on the casting yard and for the temporary bent foundation to erect large blocks at the side span of the cable-stayed bridge. Dynamic load tests were performed for quality control of these large-diameter steel pipe piles.

Scour protections with the ripraps were planned for piers of the cable stayed span and approach bridge span. Oceanographic investigations, numerical modeling, scour rate test, physical modeling with fixed bed and movable bed, and field monitoring were performed to design the scour protection around the pier. As the riprap is embanked on the seabed, Isbash's formula was used to calculate the stable weight of the riprap for scour protection under the flow. Proposed diameters of the stable stone for the piers around the SIP dolphins are 50-60 (cm) and the gradation of stones in the riprap was suggested. To secure the stability of drilled shafts and dolphins, the lateral extent and the thickness of ripraps were decided by the numerical modeling and the physical experiments. Because the calculated armor stone sizes of all the piers were smaller than the riprap size, additional execution of armor stone would not be necessary.

Figure 5. Physical modeling experiments and constructions of rip-rap embankment as scouring protections

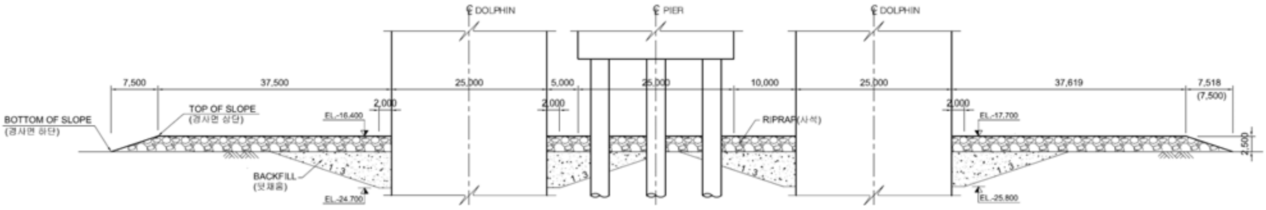


Figure 6. Cross-section of the rip-rap protection around the pier and dolphins

3. SHIP IMPACT PROTECTION SYSTEMS

Incheon Bridge was also designed to protect the bridge against the collision with navigation vessels. As provided by design specifications, all bridge components in a navigable waterway crossing, located in design water depths not less than 600 mm, shall be designed for vessel impact (AASHTO, 1994; 2007). In waterways where ship collision is anticipated, bridges shall be designed to resist ship impact forces, and/or, adequately protected by ship impact protection (SIP) systems including dolphins, berms, islands, fenders or other sacrificial devices. For the Incheon Bridge, large diameter circular dolphins are constructed at 44 locations of the both side of the main span around the piers of the cable stayed span. Figure 7 show the alignment of dolphins. In compliance with the agreements for the project and related specifications, these dolphin type SIP systems should protect the Incheon Bridge against the collision with 100,000 DWT tanker navigating the channel with speed of 10 knots. Figure 7 shows the layout and cross-section of the SIPs. Diameter of the dolphin is 25 m, or 20 m according to its location. Navigable passage width for main channel is 625.5 m under the main span deck of the cable stayed bridge and 140 m for auxiliary channel at side span behind the pylon.

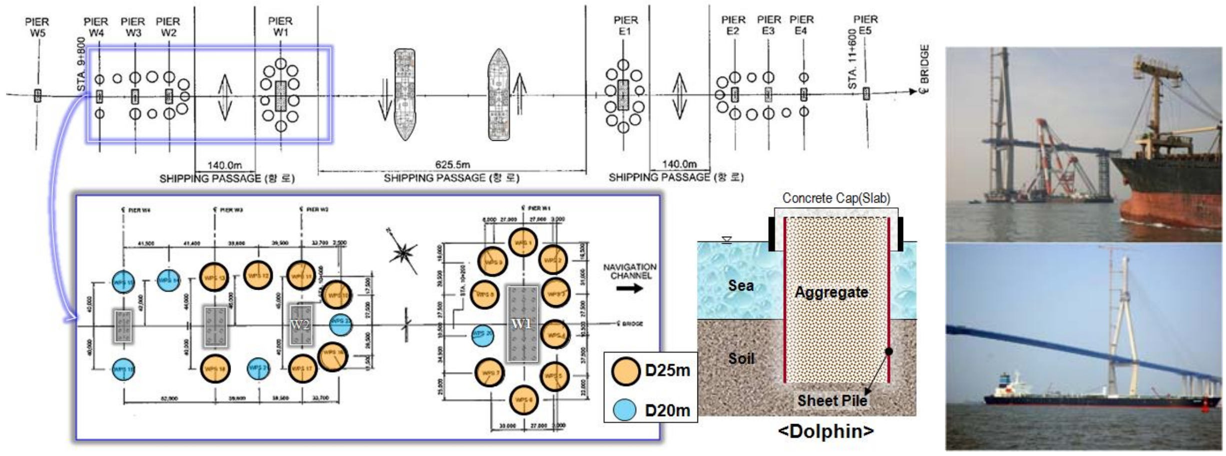


Figure 7. Layout and cross-section of the dolphins (right : large ships passing the bridge)

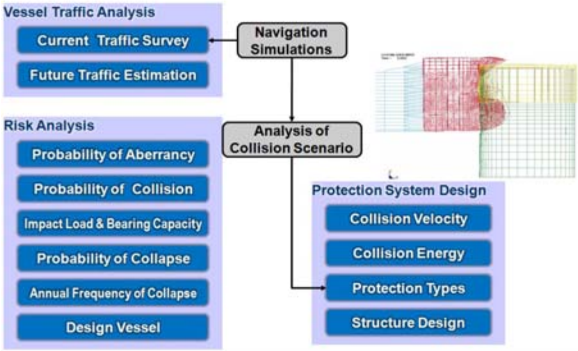


Figure 8. Flow chart of the SIP design procedure

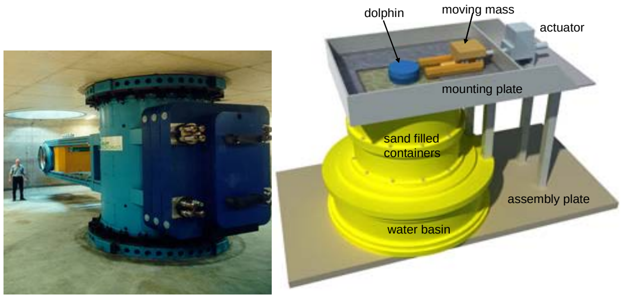


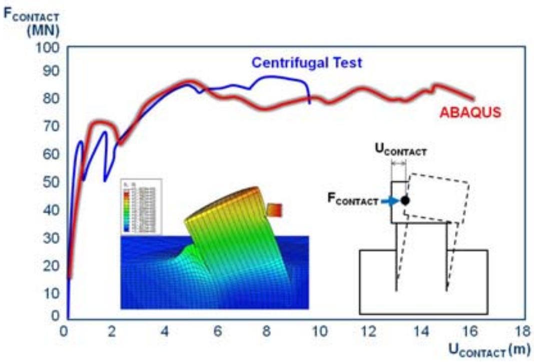
Figure 9. Geo-centrifugal testing equipment

Vessel collision risk was assessed by probability based analysis procedure on the basis of AASHTO Method II shown in Figure 8. Annual frequency of bridge collapse (AF) was computed for each bridge component and vessel classification. The AF can be taken as multiplication value of the annual number of vessel, the probability of vessel aberrancy, the geometric probability of a collision between an aberrant vessel and a bridge pier, and the probability of bridge collapse due to a collision with an aberrant vessel. For the design of the Incheon Bridge as a critical structure, the maximum AF shall be less than 0.0001. The computed AF of the Incheon Bridge through the risk analysis for 71,370 cases of the impact scenario was less than 0.5×10^{-4} and satisfies design requirements.

The SIP dolphin is the circular sheet pile web structure filled with crushed rock and closed at the top with a robust concrete cap. Yield strength of straight steel sheet pile is 355 MPa according to EN10248 and thickness is 12.7 mm. The verification of stopping capability of the dolphins therefore involves consideration of significant deformations. The design of the structure was performed with numerical analyses of which constitutional model had been verified by the physical model experiment using the geo-centrifugal testing equipment (Kim JH et al., 2007, Figure 9).

7 quasi-static and 11 dynamic model tests for 2 different prototype dolphins were carried out in a scaling of 1:200. The 3 dimensional non-linear finite element models were used to analyze the structural response and energy-dissipating capability of dolphins which is deeply embedded in the seabed. As a result of comparison between numerical analyses and model tests, a very convincing correspondence was observed along the entire displacement range and it seems that assessing dolphin behavior by FEM model give more conservative results than actual dynamic behavior (Figure 10 (a)).

The dolphin structure formed with sheet piles and filling material shall secure external stability and internal stability for ordinary loads such as wave and current pressure. Considering failure mechanism, stability assessment was performed for the strength limit state and service limit state of the dolphins. Geotechnical investigations including in-situ tests were also performed to find the engineering characteristics of the seabed soils. The friction angle of the crushed stone as a filling material was reduced to 38° considering the possibility of contracting behavior as the impact.



(a)

(b)

Figure 10. (a) Comparison of the displacement between FEA and model test (b) Dolphin constructions

4. OTHERS

The foreshore area of the construction site can be a sea, or a land according to its tidal height. The tidal difference between ebb and flow of this area is up to 9.27 m per day. This large amount of tidal difference has been the severe difficulty to overcome for civil engineers. 3 countermeasures to secure dry works in this foreshore area were the trestle method, geotextile tube method, and steel sheet piled wall method (Figure 13 (a)). Trestles were built in the sections adjacent to Yeongjong Island, while geotextile tubes and sheet pile walls were used for areas with thick marine clay deposit near New Songdo city.

(a) trestle, geotextile tube, and sheet pile wall

(b) Geotubes and sheet pile walls

Figure 11. Cofferdam systems applied to secure the dry works on the foreshore area

Figure 12. Geotextile tube constructions

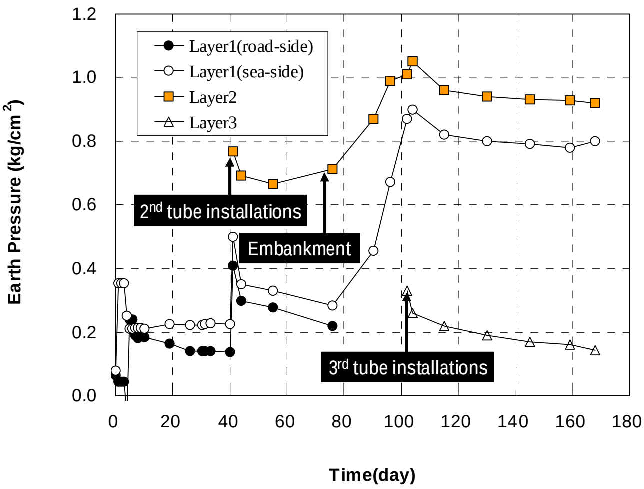


Figure 13. Earth pressure changes during the constructions

The geotextile tube method utilizes geosynthetic bags filled with backfill material to act as a structural component. Major advantages of the geotextile tube methods include its low cost, fast construction speed, and environmentally friendliness. For this project, a water-sand mixture of 80:20 by weight was used for backfill with sand forms installed between the top and bottom tubes to increase the frictional resistance. Field instrumentations were conducted to monitor the changes of the earth pressure, the pore pressure, and the deformation to ensure the stability of the tubes during construction. Figure 15 shows measured earth pressures during construction (Cho et al., 2008).

In other sections adjacent to the section adopted the geotextile tubes, sheet pile walls were used in constructing cofferdams. The sheet pile walls were designed to withstand the 10 year recurrent design wave height of 1.76 m. Two rows of sheet piles were required to meet the design requirement. The sheet pile were connected each other using tied cables. The stability of the as-designed sheet pile walls was examined using a series of finite element analysis with due consideration of possible soil-structure interaction. The sheet pile walls were constructed using low-vibration, low-noise push-in type machines in addition to traditional vibratory hammers. Field instrumentation was also implemented to check the stability against hydraulic pressure and scour.

A number of soft ground improvement techniques were employed to cope with the soft soils encountered during bridge abutment construction, such as vertical drains, Expanded Poly-Styrene (EPS) blocks, and stabilization with admixtures. Prefabricated vertical drains and/or sand compaction piles (SCP) were used to accelerate the soil consolidation settlements with horizontal fiber mats. For sections where SCPs were not implemented due to

construction constraints, the deep cement mixing (DCM) method was implemented to improve the stability against lateral spreading of the soft soil. EPS blocks were used to reduce the vertical earth pressure caused by backfilling of area behind the abutment. Also adopted were soil steel bridge using corrugated steel plates to construction open-cut tunnels. Geosynthetic reinforced soil retaining walls were also adopted in addition to top-base piles to improve load carrying capacity of foundation soil.

Figure 14. Ground improvements for the soft ground area

Figure 15. Soil steel bridge (open-cut tunnel)

Fgure 16. Steel pipe pile drivings

7. CONCLUSIONS

Incheon Bridge, 18.4 km long sea-crossing bridge, has been undertaken in a bid to establish a core infrastructure of Incheon free economic zone including the IIA and New Songdo City. The bridge will be opened to the traffic in coming October.

During planning, design, construction stages of the Incheon Bridge project, state-of-the-art geotechnologies have been adopted in various fields, such as foundations, cofferdams, ship impact protection systems, and others. Incheon Bridge is making an epoch of long-span bridge designs thanks to the fully application of the AASHTO LRFD (load & resistance factor design) to both the superstructures and the substructures.

Diverse experiences of advanced designs and constructions from the Incheon Bridge project have been propagated by relevant engineers and it is strongly expected that significant achievements in geotechnical engineering through this project will contribute to the national development of the long-span bridge technologies remarkably.

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